무배터리 무선 센서 네트워크에서의 데이터 집적 스케줄링에 관한 새로운 라우팅 구조 방법

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A Novel Routing Structure Method For Data Aggregation Scheduling in Battery-Free Wireless Sensor Networks

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요 약

The emerging energy harvesting technology, which has been successfully integrated into Wireless Sensor Networks, enables sensor batteries to be charged using renewable energy sources. In the meantime, the problem of Minimum Latency Aggregation Scheduling (MLAS) in battery-powered WSNs has been well studied. However, because sensors have limited energy harvesting capabilities, captured energy is limited and varies greatly between nodes. As a result, all previous MLAS algorithms are incompatible with Battery-Free Wireless Sensor Networks (BF-WSNs). We investigate the MLAS problem in BF-WSNs in this paper. To make the best use of the harvested energy, we build an aggregation tree that leverages the energy harvesting rates of the sensor nodes with an intuitive explanation. The aggregation tree, which determines sender-receiver pairs for data transmission, is one of the two important phases to obtain a low data aggregation latency in the BF-WSNs.

1. Introduction

Battery-Free Wireless Sensor Networks (BF-WSNs) are now being developed, and energy harvesting technologies for charging sensor batteries have been successfully integrated into Wireless Sensor Networks. When charged by solar, vibration, wireless energy transfer, and other renewable energy sources, the lifetime of BF-WSNs can be greatly extended [1]. This increases the usefulness of BF-WSNs. However, because of the limited capability of heterogeneous sensor nodes, harvested energy from the environment is limited and highly variable.. As a result, there is a growing research interest in how to use harvested energy wisely [2]-[4].

Data aggregation is a common operation in most WSN applications, where the sink expects a summary of data from the entire network. As a result, aggregation scheduling that is quick and free of conflicts is in high demand. The problem of Minimum Latency Aggregation Scheduling (MLAS) in traditional energy-abundant WSNs has been proven to be NP-hard and has been extensively studied. The MLAS problem is solved in such networks by constructing an efficient aggregation tree and generating a conflict-free schedule. Furthermore, the duty-cycled working scheme has been introduced as an efficient way of conserving energy, in which each sensor node alternates between the active and dormant states on a regular basis. For duty-cycled networks, the MLAS problem is solved by accounting for each node's active time slots in order to reduce latency.

For BF-WSNs, captured energy is still scarce and varies greatly between sensors. Before a node can transmit or receive packets, it may need to charge for an extended period of time. As a result, all the known MLAS algorithms are inapplicable to BF-WSNs. In this research, we study the MLAS problem in BF-WSNs. An aggregation scheduling scheme is usually divided into two phases which are data aggregation tree construction phase and data schedule phase based on the constructed tree in the first phase. We propose a data aggregation tree construction approach that leverages the energy harvesting rates of the sensor nodes with intuitive explanation. Together with this approach, a proper data scheduling scheme further helps to achieve a low data aggregation latency in the BF-WSNs.

The rest of paper is presented as followed. We first model the network in Section 2. Then, we proposed an algorithm to construct the aggregation tree along with sample network and constructed tree by simulation in Section 3. Finally, in Section 4, we conclude our current work and plan for the future research.

2. Network model

A battery-free wireless sensor network is formulated as an undirected graph $G = (V, E)$ where V is a set of deployed battery-free sensor nodes and E is a set of communication links between sensor nodes in the network. Every sensor node has a uniform communication range d. Two nodes u and v can communicate to each other, i.e., neighbor relationship, if $(u, v) \in E$. The link (u, v) is calculated as a Euclidean distance between u and v, $dist(u, v) \leq d$.

Each battery-free sensor is equipped with a limited capacitor E_c and we assume that it can harvest the energy from surrounding environment such as the sun, the wind, or radio frequency signal with different harvesting rate h_r. The energy consumed for transmitting and receiving data is denoted as E_t and E_r, respectively. In this paper, we exclude the energy consumed for data processing before transmitting to other intermediate nodes and sensing from surrounding environment.

There are two kinds of data conflicts might happen when sensors transmit/receives data to each other. When two sensor nodes transmit data to a same receiver, a data conflict happens at the common node, this is called primary conflict. A secondary conflict happens when a receiver overhears data from its neighbor (This neighbor node is sending data to another receiver) while receiving data from a sender. These kinds of conflicts are considered as time conflicts.

In battery-free wireless sensor networks, beside time conflicts, sensor nodes transmit or receive data only when they have enough energy in their capacitors. Therefore, allocating proper sender-receiver pairs (child-parent pairs) for data transmission further reduce the total data aggregation time. The conflicts that prevents data transmissions due to insufficient energy capacity at the sensor nodes, are called energy conflicts.

In this research, a conflict-free data schedule with minimal latency for battery-free sensor network is studied. In which we schedule the time for node u transmit data to node v. Node u is the sender considered as a child node and node v is the receiver considered as a parent node of node u.

3. Routing structure construction algorithm

A conventional data scheduling is usually divided into two phases. The first phase is routing structure building where we adopt parent-child pairs for battery-free sensor nodes. The parent-child pair establishes receiver-sender nodes, respectively. The second phase is data scheduling based on the constructed routing structure, in which we plan the time that a sender (child node) transmits data to its receiver (parent node) with conflict-free.

Algorithm 1 shows the procedures to build the routing structure based on the energy harvesting rates of battery-free sensors. The algorithm takes the communication graph G consisting of V nodes and E edges, the consumed energy E_r of a node when it receives data and the energy harvesting rate h_r of battery-free sensors as inputs. An aggregation tree T consisting of $V_T = V$ sensor nodes and a set E_T links is returned as an output.

Algorithm 1: Aggregation Tree Construction algorithm

```
Input: $G = (V, E)$, sink $s \in V$, $E_r$, $h_r$
        //$E_r$: Consumed energy for receiving data
        //$h_r$: Energy harvesting rate of a node
Output: An aggregation tree $T = (V_T, E_T)$
1.  $V_T = \{s\}; E_T = \emptyset$
2.  for $v$ in $V$ do
3.      $r_v = h_r$
4.  Divide all nodes in the graph layer by layer based on the hop
    distance to the sink (from layer $L_0$ to layer $L_R$)
5.  for $l_i = 1$ to $L_R$ do
6.      $R_l = \{$All nodes at layer $l_i\}$
7.      while $R_l \neq \emptyset$ do
8.          $u \leftarrow$ Random selected in $R_l$
9.          if $N(u) \cap l_{i-1} = v$ then
10.             $C(v) \leftarrow C(v) \cup \{u\}$
11.             $P(u) = v$
12.             $r_v = \frac{h_r}{|C(v)| * E_r}$
13.             $V_T \leftarrow V_T \cup \{u\}$; $E_T \leftarrow E_T \cup \{(u, v)\}$
14.             $R_l \leftarrow R_l \backslash \{u\}$
15.         if $N(u) \cap l_{i-1} = F$ then
16.             Sort all nodes in set $F$ in non-increasing order of
                their residual ratio $r$
17.             $v =$ The first node in set $F$
18.             $C(v) \leftarrow C(v) \cup \{u\}$
19.             $P(u) = v$
20.             $r_v = \frac{h_r}{|C(v)| * E_r}$
21.             $V_T \leftarrow V_T \cup \{u\}$; $E_T \leftarrow E_T \cup \{(u, v)\}$
22.             $R_l \leftarrow R_l \backslash \{u\}$
23. Return $T = (V_T, E_T)$
```

Initially, the tree T starts with set V_T containing only the sink and set E_T as an empty set (line 1). We use a metric named r_v as residual energy ratio of node $v, v \in V$. The residual energy ratio r_v of node v is defined as a ratio of energy harvesting rate h_r of node v to the total consumed energy when the node receives the data from its children:

$$r_v = \frac{h_r}{|C(v)| * E_r} \tag{1}$$

Where h_r is the energy harvesting rate of node v, $C(v)$ is the set of child nodes of node v, E_r is energy consumed when node v receives data.

In the BF-WSNs, beside time conflicts, the data scheduling also depends on the residual energy at the sensors. Assigning many child nodes to a node that has low energy harvesting rate create a bottleneck at the parent node, because the child nodes must wait the parent node harvest enough energy to perform the data communication. As a result, the total data aggregation latency becomes larger due to waiting time of child nodes at the low energy harvesting rate parent node. Therefore, the intuitive idea of using this metric is to assign more child nodes to the sensor that has high energy harvesting rate when building the aggregation tree. Although the data communication of a node consumes the energy when it transmits and receives data, every sensor node has only one parent but different number of child nodes. Therefore, the residual energy ratio used in this paper depends on the energy harvesting rate and the consumed energy when the node

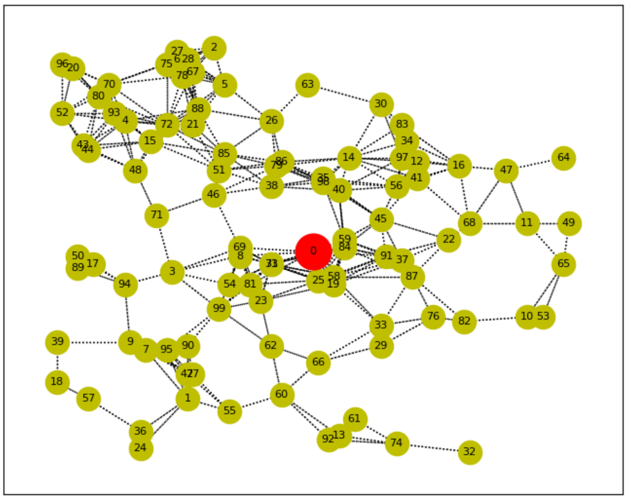

Figure 1: A sample network topology. The dash lines present communication links between battery-free sensor nodes

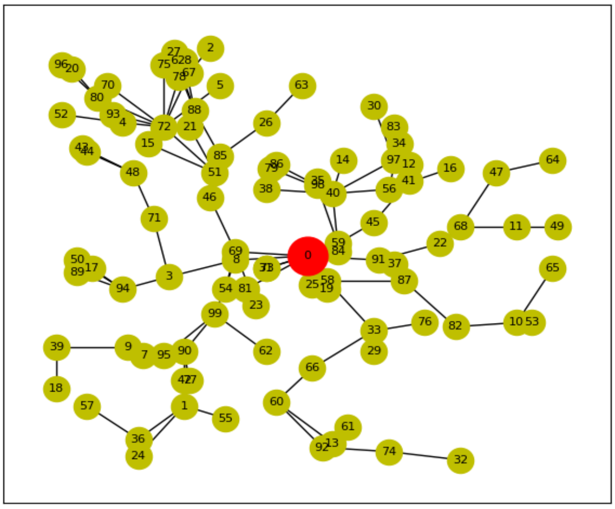

Figure 2: Aggregation tree based on energy harvesting rate of sensor nodes. The solid lines present transmission links between battery-free sensor nodes

receives data.

At the beginning all nodes in the network have not been assigned any child nodes yet, so that we assign the initial value of residual ratio equal to the energy harvesting rate (lines 2-3). Based on the hop distance from a specific node to a sink, the algorithm divides the network into $(R+1)$ layers, i.e., from L_0 to L_R (line 4). It means that the sink is at layer L_0. After that, the algorithm starts constructing the aggregation tree layer by layer in top-down manner (lines 5-22).

At each layer l, a set R_l includes all nodes at layer l (line 6), these nodes are not assigned parents yet. Each node u in set R_l is randomly selected (line 8), the algorithm checks if there is any neighbor of u in the previous layer, i.e., l_i (All nodes in this layer are already added to the tree). If node u has only one neighbor, i.e., v, in the upper layer, u adopts that node v as its parent. Then the residual energy of v is updated since v has a new child node u. The aggregation tree is updated by adding u into the node set, and the link (u, v) is added to the set E_T. After that, node u is removed from the set R_l since it has the parent (lines 9-14).

If node u has more than one neighbor in the upper layer, i.e., these neighbor nodes are in a set F, the algorithm sorts the nodes in set F in non-increasing order of their residual energy ratio. A node v, which has the highest value of residual energy ratio in F, is selected to be parent of u (lines 18-19). Then, the residual energy ratio r is updated since it has one more child node. The aggregation tree is updated by adding u and the link (u, v) into it. Set R_l removes u after it is assigned the parent (lines 15-22). The process of assigning child-parent pairs (sender-receiver pairs) operates until the lowest layer L_R is reached, at that time all nodes in the network, except the sink assigned the parents.

We simulate a battery-free sensor network consisting of 100 battery-free sensor nodes randomly distributed in an area 100x100m^2 using Networkx in Python [5] as shown in Figure 1. The sink node is deployed at the center of the area and responsible for the computation so that it has unlimited power source. Initially, all sensor nodes have no energy in their capacitor at the time they are deployed. We assume that the sensor nodes harvest the energy from the radio frequency signal, the rate is varied from $1\mu J/s$ to $200\mu J/s$ as claimed by [6]. The consumed energy for transmitting and receiving data of a Mica2dot sensor node are E_t = 59.2 $\mu J/s$, and E_r = $28.6\mu J/s$, respectively, according to [7]. Figure 2 presents the achieved aggregation tree based on residual energy ratio of sensor nodes.

4. Conclusion and Future work

In this paper, we proposed an aggregation tree construction approach for a battery-free wireless sensor network in a top-down manner. The proposed approach bases on the energy harvesting rate of sensor nodes expecting to reduce the data scheduling delay due to waiting time at low energy harvesting rate nodes. We present the intuitive idea for using the energy residual ratio metric and present the sample network with obtained aggregation tree by a simulation. With this proposal, we plan to adopt a scheduling method as the second phase of data scheduling purposing to achieve a low data aggregation latency in our future research. In addition, we will compare our work with state-of-the-art schemes which are also working on minimizing the time for data aggregation in the battery-free sensor networks.

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References

[1] Yang, Shusen, Yad Tahir, Po-yu Chen, Alan Marshall, and Julie McCann. "Distributed optimization in energy harvesting sensor networks with dynamic in-network data processing." In *IEEE INFOCOM 2016-The 35th Annual IEEE International Conference on Computer Communications*, pp. 1-9. IEEE, 2016.

[2] Chen, Kunyi, Hong Gao, Zhipeng Cai, Quan Chen, and Jianzhong Li. "Distributed energy-adaptive aggregation scheduling with coverage guarantee for battery-free wireless sensor networks." In *IEEE INFOCOM 2019-IEEE Conference on Computer Communications*, pp. 1018-1026. IEEE, 2019.

[3] Wang, Cong, Ji Li, and Yuanyuan Yang. "Low-latency mobile data collection for wireless rechargeable sensor networks." In *2015 IEEE International Conference on Communications (ICC)*, pp. 6524-6529. IEEE, 2015

[4] Chen, Quan, Hong Gao, Zhipeng Cai, Lianglun Cheng, and Jianzhong Li. "Energy-collision aware data aggregation scheduling for energy harvesting sensor networks." In *IEEE INFOCOM 2018-IEEE Conference on Computer Communications*, pp. 117-125. IEEE, 2018.

[5] Networkx. https://networkx.org/

[6] Lu, Xiao, Ping Wang, Dusit Niyato, Dong In Kim, and Zhu Han. "Wireless networks with RF energy harvesting: A contemporary survey." *IEEE Communications Surveys & Tutorials* 17, no. 2 (2014): 757-789.

[7] Wander, Arvinderpal S., Nils Gura, Hans Eberle, Vipul Gupta, and Sheueling Chang Shantz. "Energy analysis of public-key cryptography for wireless sensor networks." In *Third IEEE international conference on pervasive computing and communications*, pp. 324-328. IEEE, 2005.